Geomorphic impacts, age and significance of two giant landslide dams in the Nepal Himalayas: Ringmo-Phoksundo (Dolpo District) and Dhampu-Chhoya (Mustang District).

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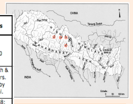
1. INTRODUCTION: MAIN ISSUES

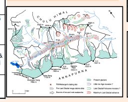
Large catastrophic slope failures have recently retained much attention in the northern dry Himalayas *(Hewitt 2009)*. They play a prominent role in the denudation history of active orogens at a wide range of spatial and time scales *(Korup & Clague, 2009)*, and they impact durably landforms and process evolution in upstream catchments. Their occurrence mostly results from three different potential triggers: earthquakes, post-glacial debuttressing, and permafrost melting. We focus on two examples of giant rock slope failures that occurred across and north of the Higher Himalaya of Nepal and assess their respective influence on the regional, geomorphic evolution.

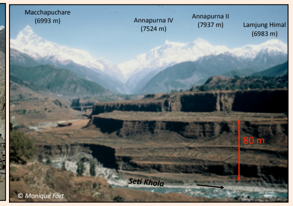
From Fort, 2011 —>

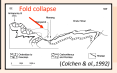
	Mass wasting failure	Volume (10^8 m^3)	Age	Geological context	Type of failure	Nature of material	Geomorphic impact	References
1	Phoksumdo-Ringmo rockslide (Suli Gad valley)	15	Presumably 30-40,000 yr (no dating)	NHTS (limestones)	In situ collapse	Disintegrated, recemented fragments and blocks	landslide dam lake, volume: 1500 Mm^3	Yagi 1997; Ibetsberger & Weidinger 2000
2	Dhumpu-Kalopani rock-avalanche (Kali Gandaki)	30	29,674 +/- 1022 yr (^{10}Be); 4,1 +/- 0,6	HHC (augen and biotitic gneisses)	Banc-to-banc rock-slide rock-avalanche	bedrock slabs + breccia and pulverized rocks	landslide dam lake of Marpha, volume: 4000 M m^3	Fort 2000; Zech & alii, 2009 + pers. unpubl. dates by D. Bourlès et al.
3	Pokhara giant rock-avalanche/debris flow (Seti khola)	40	500 yr +/- 100 (^{14}C)	HHC Crystallines (gneisses) + NHTS + tills	Catastrophic collapse of Higher Himalayan Thrust Front	Gigantic debris flow (channelized along the Seti khola gorges)	Damming of adjacent, tributary valleys (lakes)	Fort 1987, 1988; Fort & Peulvast 1995
4	Manang rock-avalanche (Upper Marsyangdi khola)	150	Interstadial ? Pre-Last Glacial advance	NHTS (marly and hard limestones)	Catastrophic collapse of recumbant fold axis	diamicton (all clast sizes), recemented breccia	linear, gully erosion + karstic like landforms	Fort 1993; Weidinger 2006;
5	Dhikur Pokhari rockslide (Upper Marsyangdi khola)	10	Post Glacial	NHTS (limestones and schists)	In situ collapse	Brecciated cataclastic and recemented blocks	shallow, relict Dhikur pokhari (lake)	Korup & alii, 2006
6	Latamrang landslide (Upper Marsyangdi khola)	> 55 (1 already removed)	5400 yr BP	HHC Crystallines (gneisses) + NHTS + tills	Sledge-like sliding	Brecciated cataclastic and recemented blocks	landslide dam lake, volume 160 M m^3	Korup & alii, 2006
7	Tsergo Ri rockslide (Langtang khola)	100	34,2 +/- 10,4 (10 Be); 25-40 (TL) 51+/-13 (FT)	HHC (gneisses and intrusive granite)	Post glacial gravity instability	Microbreccia (mylonites and pseudotachylites)	Linear, gully erosion	Barnard & al., 2006; Weidinger & alii, 2002; Takagi & alii, 2007
8	Khumjung rock-avalanche (Upper Dudh Kosi)	21	Pre-Last Glacial advance	HHC (gneisses)	Post glacial gravity instability	Brecciated cataclastic, blocks		Heuberger, 1986



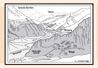
8 massive landslides (volume > 1 km^3) reported in Nepal *(Fort, 2011)*. Right: Manang (# 4)







Trigger: sismo-tectonic event + glacial debuttressing

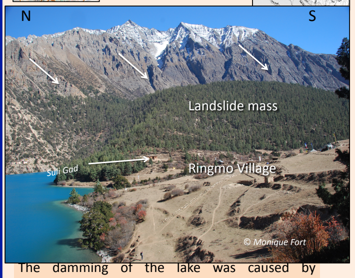


The Pokhara gravels fill (#3): result of a gigantic rock-avalanche 500-years old. Mechanism? Catastrophic collapse of the Annapurna IV (thrust) front, possibly seismically triggered in 1505 *(Fort 1987; 2010)*

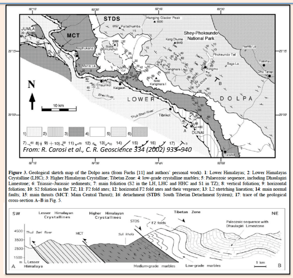
2. DATING METHODS: COSMIC RAY EXPOSURE DATING

AMS measurements of the ^{36}Cl and ^{10}Be concentrations were performed at the 5 MV national AMS facility ASTER located at CEREGE, Aix en Provence, France. All ^{36}Cl concentrations were normalized to the KNSTD1600 calibration material ($^{36}Cl/^{35}Cl$ $=1.6*10^{-12}$ provided by K. Nishiizumi) and all ^{10}Be concentrations were normalized to the SRM 4325 NIST reference material with an assigned $^{10}Be/^{9}Be$ value of $(2.79\pm0.03)*10^{-11}$. The ^{36}Cl decay constant of $(2.303 \pm 0.016)*10^{-6}$ a^{-1} corresponds to a half-life ($T_{1/2}$) of $(3.014\pm0.021)*10^{5}$ years and the ^{10}Be decay constant of $(4.987\pm0.036)*10^{-7}$ a^{-1} to a half-life of $(1.39\pm0.01)*10^{6}$ years. Analytical uncertainties include the counting statistics, machine stability (~0.5%) and blank correction, the associated $^{36}Cl/^{35}Cl$ blank ratio being ~10^{-14} and the $^{10}Be/^{9}Be$ blank ratio ~$2*10^{-15}$. Cosmic ray exposure ages derived from these cosmogenic nuclide concentrations were calculated using production rates corrected for topographic shielding following *Dunne et al. (1999)* and scaled to the sites position (latitude, altitude) using the Stone scheme *(Stone, 2000)* from a sea level and high latitude production rate of 4.5±0.3 atoms of ^{10}Be $g_{(SiO2)}^{-1}.yr^{-1}$ for ^{10}Be and integrating all production pathways (spallation, including a spallation production rate of 42.0 ± 2.0 atoms of ^{36}Cl g^{-1}_{Ca} yr^{-1} and at sea level and high latitude, thermal neutron, muon captures and radiogenic production) and the rock's chemical composition for ^{36}Cl.

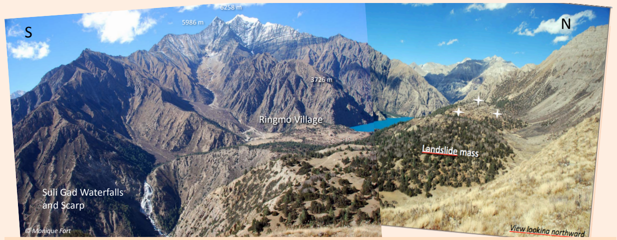
3. RINGMO-PHOKSUNDO SITE



The damming of the lake was caused by rockslides bodies derived from different parts of the rocky face bounding the lake in its SE part.



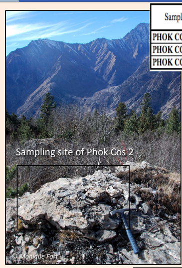
The Phoksumdo lake (3600 m asl.; area of 4.5-to-5 km^2) is the second largest lake of Nepal; it owes its origin to the damming of the Suli Gad River by the large (4.5 km^3) collapse of a mountain wall (Dhaulagiri limestones) culminating at 5148 m, SE of the lake *(Fort & Rimal 2010)*. According to *Yagi (1997)*, the collapse may have occurred 30 to 40 ka, an interpretation revised by this study.



The landslide morphology presents a series of mounds (metres to tens of metres high) and depressions of varying size. Its mass is composed of large blocks of massive dolomites found as far as west of Ringmo Village and down to the southern rim of the landslide dam.

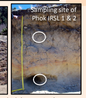
Most of the Suli scarp is uphold by limestones outcrops, but along the central part, the former Phoksund gorge is filled in by dark grey, fine sediments (till material) and overlain by orange conglomerates (including dolomites boulders), then by yellowish, unsorted conglomeratic material blocks and calcareous silty matrix). **The presence of glacial till at the very base of the sequence suggests the rockslide event is post-glacial.**

Sample ID	Sample weight dissolved [g]	% CaO	^{36}Cl / ^{35}Cl (10^{-14})	$^{35}CL/^{37}Cl$	Cl [ppm]	^{36}Cl [10^{5} at/g]	Exposure Age of surface (uneroded surface)	Uncertainties
PHOK COS 1	67,29	55,18%	133,8	35,64	2,79	6,8	6987	566
PHOK COS 2	69,08	54,70%	382,0	24,08	4,58	19,8	20882	1687
PHOK COS 3	72,015	54,59%	314,8	10,42	13,82	19,5	20888	1661



Two consistent ^{36}Cl ages of 20,885 ±1675 argue for a single, massive event of paraglacial origin

Field assumptions are confirmed by cosmic ray exposure dating: the landslide dam was formed in response to the collapse of the limestone cliff in one single, massive event. The ^{36}Cl dates confirm the paraglacial/post-glacial origin of the failure, an event that fits well with the last chronologies available on the Last Glacial Maximum in the Nepal Himalaya *(Owen & Dortch 2014)*. IRSL dating of silts suggests a progressive trend to dryness of these Northern Himalayan regions from Late Pleistocene to Holocene.

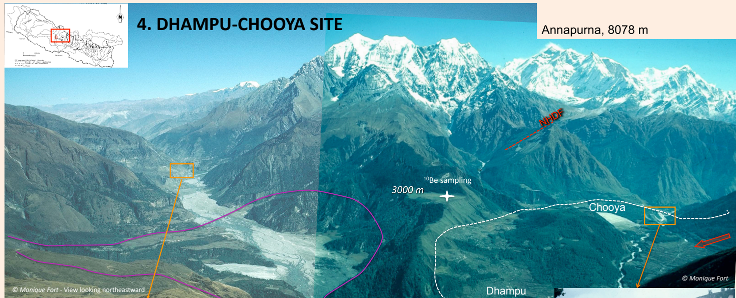


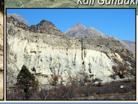
The coarse debris is widely mantled by a thick (up to 10 m) cover of silts, well prominent downstream above the Suli Gad gorges.

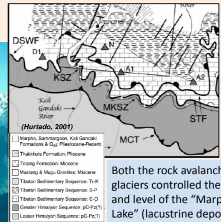
Note on Infrared Stimulated Luminescence (IRSL) dating

The IRSL samples, PHOK 2 and PHOK 1, were collected respectively at the top and the bottom of the silty deposit, below the surface soil. IRSL measurements were performed at Montreal laboratory by S. Balescu, S. Huot and M. Lamothe. The corrected IRSL ages of PHOK 2 and PHOK 1, respectively 4.7 ± 0.3 ka and 12.6 ± 0.7 ka, are stratigraphically consistent *(Fort et al., 2013)*.

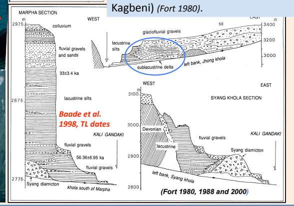
4. DHAMPU-CHOOYA SITE







Both the rock avalanche and glaciers controlled the existence and level of the "Marpha Lake" (lacustrine deposits up to Kagbeni) *(Fort 1980)*.

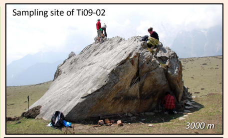


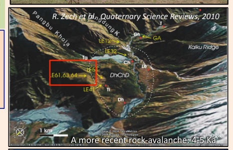
The Dhampu-Chhoya rock avalanche (10^9 m^3, area extent 10 km^2) was derived from the northward failure of the Kaiku ridge, uphold by north-dipping, upper crystal-lines of the Higher Himalaya *(Fort 1974; 2000)*. It dammed the Kali Gandaki River, with complex interactions with the Late Pleistocene ice tongues derived from the Dhaulagiri (8167 m) and Nilgiris (7061 m) peaks.

Be-10 cosmic ray exposure ages (CEREGE, *Gribenski 2010*)
Ti09-01 : 29 674 ± 1 022 ka
Ti09-02 : 24 844 ± 628 ka
Ti09-03 : 29 694 ± 1 011 ka

The discrepancy in the dating of both lacustrine and failure events raise the issue of the nature of the lacustrine dam: (i) rock-avalanche as initially thought (*Fort 1974; 1980; Baade 2000*) or (ii) possibly a glacial tongue controlling the lake level *(Fort and Cossart 2013)*; (iii) repeated failures cannot be ruled out *(Zech et al. 2010)*.

Sampling site of Ti09-02





The fact that both *Zech et al*. (2009) and our team (*Fort et al., in prep.*) have obtained consistent exposure duration to cosmic ray, from different samples and different laboratories, provides very good evidence of a chronologically, well constrained Dhumpu-Chhoya rock-avalanche event, i.e. about 30,000 years ago. Conversely, dating of lacustrine sediments has not been cross-checked to date, and some uncertainty cannot entirely be ruled out.

5. COMPARISONS and CONCLUDING REMARKS

Phoksundo-Ringmo

- Efficient drainage blockage, but no backwash sedimentation (predominant carbonates + low discharge)
- Prominant knick point: karst + boulder pavement reducing incision => prominent hanging valley
- Triggering factor: glacial retreat («paraglacial collapse»), cf. ^{36}Cl dates

Dhampu-Chooya

- Efficient drainage blockage, and extensive lacustrine sedimentation (glacial sediment reworking + Spiti shales + glacial- and snow-melt discharges)
- Knick points and associated epigenetic gorges + braided Kali Gandaki valley: delayed incision => relatively hanging valley
- No climate forcing, cf. ^{10}Be dates => Triggering factor related to the North Himalayan Detachment Fault + foliation dip of Upper Himalayan Gneisses
- Complex interplay between glaciers and mountain wall collapses *(Fort 2000)*

Both examples confirm that giant landslides play a significant role in the:

- Destruction of Himalayan topography *(Fort 1988)*,
- Bedrock protection from river incision *(Korup et al. 2010)*,
- Delay of sediment transport outward from the mountain zone (cf. sediment storages & budgets; *Fort & Cossart 2013; Blöthe J. & Korup O., 2013*)
- Local controls exerted by topography and climate (eg. magnitude of glacia-tion + snow <—> discharge) + lithology (eg. sediment supply <—> storage)

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